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F. Lin, S.Y. Lee, Indiana University, Bloomington, IN 47405, USA
L.A. Ahrens, M. Bai, K.A. Brown, E.D. Courant, J.W. Glenn,
H. Huang, A.U. Luccio, W.W. MacKay, T. Roser, N. Tsoupas,
BNL, Upton NY 11973 USA

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Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

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INVESTIGATION OF RESIDUAL VERTICAL INTRINSIC RESONANCES WITH DUAL PARTIAL SIBERIAN SNAKES IN THE AGS*

F.Lin, S.Y.Lee
Indiana University, Bloomington, IN 47405, USA
L.A.Ahrens, M.Bai, K.A.Brown, E.D.Courant, J.W.Glenn, H.Huang, A.U.Luccio
W.W.MacKay, T.Roser, N.Tsoupas
Brookhaven National Laboratory, Upton, NY 11973, USA

Abstract

Two partial helical dipole snakes were found to be able to overcome all imperfection and intrinsic spin resonances provided that the vertical betatron tunes were maintained in the spin tune gap near the integer 9. Recent vertical betatron tune scan showed that the two weak resonances at the beginning of the acceleration cycle may be the cause of polarization loss. This result has been confirmed by the vertical polarization profile measurement, and spin tracking simulations. Possible cure of the remaining beam polarization is discussed.

INTRODUCTION

During the acceleration of the polarized proton beam in the AGS, numerous depolarizing spin resonances cause spin polarization loss when the spin precession frequency equals the frequency of the spin perturbing magnetic field. Two important types of spin resonances are the imperfection resonance driven by the vertical closed orbit errors in quadrupoles, and the vertical intrinsic resonance driven by the vertical betatron motion in quadrupoles. The imperfection resonances happen at $\nu_{sp} = G\gamma = n$, where $G = (g-2)/2 \approx 1.7928$ is the proton anomalous gyromagnetic g-factor, $\gamma = \frac{E}{mc^2}$ is the Lorentz factor and n is an integer. The strong intrinsic resonances happen at $G\gamma = kP \pm \nu_y$, where n and k are integers, ν_y is the vertical betatron tune and P is the super-periodicity of the machine lattice, 12 for AGS. In the AGS seven strong intrinsic resonances can cause partial spin flips resulting in depolarization.

In order to overcome the spin resonances, a local spin rotator, called Siberian snake[1], is used to maintain the spin polarization. Snakes cause the spin vector to precess by an angle of less than or equal to 180^0 around an axis in the horizontal plane. With one snake of strength χ in an otherwise perfect circular accelerator, the spin tune ν_{sp} becomes

$$\nu_{sp} = \frac{1}{\pi}\arccos(\cos\frac{\chi\pi}{2}\cos G\gamma\pi), \qquad (1)$$

which is dependent on the snake strength χ and beam energy γ. A full Siberian snake corresponds to $\chi = 1$ and partial Siberian snake is $\chi < 1$. When the $G\gamma$ is close to an integer, the spin tune ν_{sp} is shifted away from the integer by $\pm\frac{\chi}{2}$. Thus the snake can overcome the imperfection resonance successfully provided the resonance strength is much smaller than the spin tune gap generated by the snake. For medium energy synchrotron such as AGS, the partial snake is more practical due to the lack of long straight sections.

In the AGS, two partial helical dipole snakes are separated by $1/3$ of the ring to eliminate the spin mismatching at the injection and extraction energy. Hence, the spin tune is given by[2],

$$\nu_s = \frac{1}{\pi}\arccos(\cos\frac{\chi_c}{2}\cos\frac{\chi_w}{2}\cos[G\gamma\pi] - \sin\frac{\chi_c}{2}\sin\frac{\chi_w}{2}\cos[G\gamma\frac{\pi}{3}]), \qquad (2)$$

where χ_c, χ_w are the spin rotation angles caused by the cold and warm snake, respectively. The deviation of spin tune from an integer reaches its maximum every $G\gamma = 3n$, where n is an integer. Since the AGS has a superperiodicity of 12 and the vertical betatron tune is close to integer 9, this feature provides the maximum space for placing the vertical betatron tune in the prohibited region of spin tune at all the strong vertical intrinsic resonances. The resonance free spin tune gaps at all other integers are large enough for avoiding all weak vertical spin resonances.

RESIDUAL VERTICAL INTRINSIC RESONANCES

The polarized proton beam in the AGS is injected at energy $G\gamma = 4.5$ and extracted at energy $G\gamma = 45.5$. With the 2.1T cold snake and 1.53T warm snake, 65% polarization was measured at the AGS extraction energy comparing to the injected 82%. Except for the polarization loss due to horizontal intrinsic resonances[3], the vertical motion could also introduce spin depolarization to the proton beam.

The spin tune gap generated by the two partial helical dipole snakes is large enough to overcome the imperfection resonances and intrinsic resonances. The challenge is to push the vertical betatron tune close to an integer. At low energies, the helical magnets in the two partial snakes cause significant betafunction distortion. Therefore, four compensation quadroples are added to each of the two partial snakes to keep the β function unchanged at the entrance

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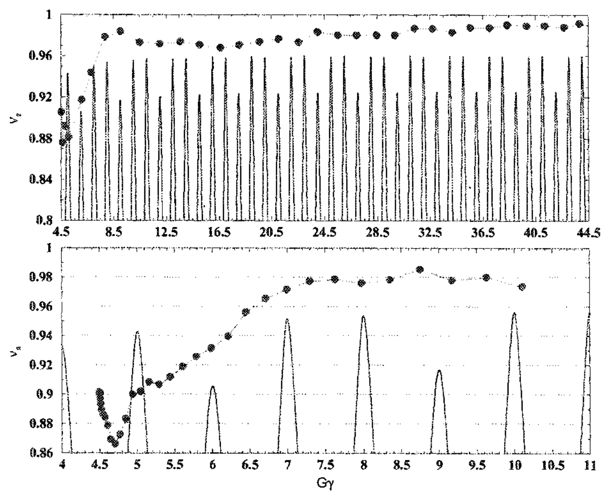

Figure 1: Spin tune and the fractional part of the measured vertical tunes (dots connected by the dash line) with 2.1T cold snake and 1.53T warm snake as a function of $G\gamma$. The upper plot shows during the whole energy ramping and the bottom one is at the beginning region of the acceleration.

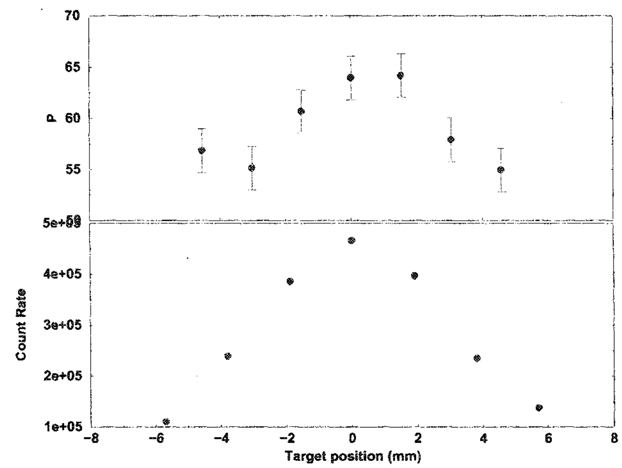

Figure 2: The vertical polarization profiles (upper) and vertical beam profiles (bottom) with 2.1T cold snake and 1.53T warm snake at the AGS extraction energy $G\gamma = 45.5$.

and exit of super-period section containing snakes. Due to the compensation quadroples, the vertical betatron tune can be pushed into the spin tune gap only after $G\gamma = 5$, leaving two intrinsic resonances unovercome at the beginning of acceleration. In Fig.1, the upper plot gives both spin tune and the fractional part of the measured vertical tune path during the energy ramping with 2.1T cold snake and 1.53T warm snake in the AGS. One detailed vertical tune measurement at the beginning of the acceleration is shown at the bottom of Fig.1. Although the two intrinsic resonances are weak, some modest polarization loss could still be caused because of the low acceleration rate.

Since the intrinsic resonance strength is proportional to the square root of the particle emittance I[4]

$$|\epsilon(I)|^2 = |\epsilon(I_0)|^2 \frac{I}{I_0}, \tag{3}$$

where I_0 is the rms emittance of the beam and $\epsilon(I_0)$ is the rms value of resonance strength, a higher polarization is expected with smaller emittance. Therefore, a polarization profile in the vertical plane can develop due to the vertical spin resonances because of different polarizations for particles with different vertical emittances. This vertical polarization profile was measured by placing the horizontally oriented carbon target at different vertical positions inside of the beam.

Fig.2 shows one vertical polarization profile measurement and the corresponding vertical beam profile for 2.1T cold snake and 1.53T warm snake. If all the vertical tunes during the acceleration cycle were moved into the spin tune gap, the polarization profile was expected to be flat wherever the target was placed vertically in the beam, meaning the measured polarization independent to the particle emittance. However, the curvature of the polarization profile showed the depolarization of the beam due to the vertical betatron motion. The spin resonance could happen at low energies where the vertical tune was outside of the spin tune gap, as shown at $G\gamma = 4.92$ and $G\gamma = 5.08$.

Simulation of spin tracking using the program SPINK[5] was performed according to the measured vertical tune path. The tracking started with 100 Gaussian distribution particles in the vertical phase space with normalized rms emittance $2.5\mu m$ and a rms momentum spread $\frac{\Delta p}{p} = 0.003$. The horizontal emittance was set zero to avoid any depolarization effect from the horizontal motion. The real acceleration rate of the AGS machine was used and the initial spin direction was put along the stable spin direction to eliminate any polarization loss due to spin mismatching. Fig.3 shows the beam polarization after crossing the two weak intrinsic resonances with 2.1T cold snake and 1.53T warm snake. This simulation confirmed polarization drops at the two intrinsic resonances due to the vertical motion as expected. The total loss from these two resonances was about 4% of the intial polarization.

PROSPECT

From the Froissart Stora formula[6], the beam polarization after crossing an isolated resonance is given by

$$P = \frac{1 - \frac{\pi|\epsilon|^2}{\alpha}}{1 + \frac{\pi|\epsilon|^2}{\alpha}}. \tag{4}$$

Under the same resonance condition, a faster resonance crossing rate α leads to higher polarization transmission. Hence, raising the effective resonance crossing rate is an approach to reduce the polarization loss.

Based on this idea, the spin tracking was carried out from the simulation first. The effective resonance crossing rate α, which equals acceleration rate α_0 if the vertical

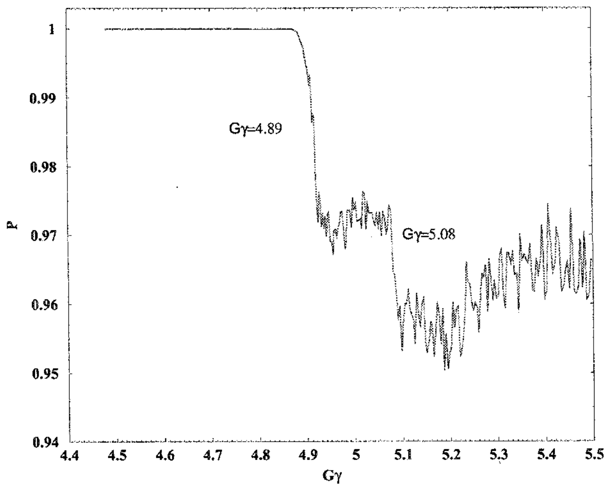

Figure 3: Spin tracking throughout the first two weak intrinsic resonances with 2.1T cold snake and 1.53T warm snake. The polarization is obtained along the stable spin direction.

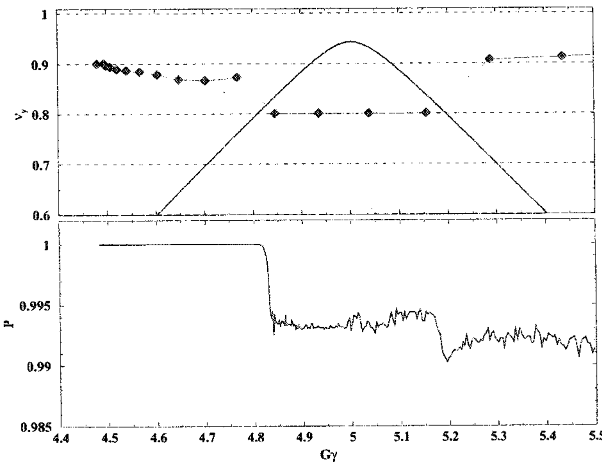

Figure 4: Spin tracking throughout the first two weak intrinsic resonances with the varied vertical tune path. The upper plot is the set vertical tune path and the bottom one is the polarization as function of $G\gamma$.

tune stays constant, can be promoted by changing the vertical tune during acceleration. With the varied vertical tune crossing the spin resonance, the effective resonance crossing rate α is given by

$$\alpha = \frac{d(G\gamma - \nu_y)}{d\theta} = \alpha_0 - \alpha_0 \cdot \frac{d\nu_y}{dG\gamma}. \tag{5}$$

Here α_0 is the acceleration rate coming from the main magnetic field function. The negative slope of $\frac{d\nu_y}{dG\gamma}$ expresses how much the α has been enhanced.

One spin tracking with the promoted resonance crossing rate is shown in Fig.4. The upper plot is the given vertical tune path crossing the two resonance and the bottom one is the resultant polarization projected to the spin spin direction. With the same acceleration rate of the real machine lattice, the polarization loss can be reduced to less than 1% with the raised effective resonance crossing rate α.

CONCLUSION

By moving the vertical betatron tune into the spin tune gap generated by two partial helical dipole snakes in the AGS, the polarization of a proton beam has been maintained successfully. However, the curvature in the vertical polarization profile with 2.1T cold snake and 1.53T warm snake still shows the effect of vertical motion on the polarization. The vertical tune scan proved the existence of two weak intrinsic resonances at early acceleration. Since the acceleration rate is also slow, a modest polarization drop can happen. The simulation of spin tracking crossing the two intrinsic resonances, performed by using the real machine situation, confirmed the polarization loss. An approach of reducing the polarization drop is to raise the effective resonance crossing rate, which can be realized by pushing the vertical tune path orthogonal to the spin tune path. With the increased resonance crossing rate, the polarization can be improved greatly. This gives us a guide to preserve the polarization with the two weak intrinsic resonances left due to the compensation quadroples for the snakes during the energy ramp.

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